

3D Disc Asymmetry in Adolescent Idiopathic Scoliosis

Anna Iacocca¹, Jacob Jordan², Thomas Coleman², Patrick Cahill², Axel Moore¹
¹Carnegie Mellon University, Pittsburgh, PA, ²Children's Hospital of Philadelphia, Philadelphia, PA
aiacocca@andrew.cmu.edu

Disclosures: Anna Iacocca (N), Jacob Jordan (N), Thomas Coleman (N), Patrick Cahill (5-Pediatric Spine Foundation & Setting Scoliosis Straight Foundation, 6-Dynamic lung MRI, 8-JBJS, 9-POSNA & SRS), Axel Moore (N)

INTRODUCTION:

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity that typically manifests during periods of rapid skeletal growth. While its etiology is multifactorial and remains poorly understood, the progressive nature of the deformity has been suggested to follow the Hueter-Volkman law, which states that asymmetric loading over a bone's growth plate leads to differential longitudinal growth. In the AIS spine there is asymmetric growth of the vertebral bodies which leads to a coronal plane deformity—the hallmark of AIS. This vertebral wedging has been well-documented in AIS and is known to contain a large fraction of the spinal deformity; however, the impact of AIS on the intervertebral disc (disc), a key structure for transmitting load between adjacent vertebrae and imparting flexibility to the spine, remains understudied. Given increasing efforts to develop correction procedures that preserve the disc's health and function, it is critical to characterize how AIS affects the disc's structure. This study aimed to quantify the 3D structure of discs from AIS patients, with a hypothesis that AIS discs are asymmetric in multiple dimensions.

METHODS:

Following IRB approval, we retrospectively analyzed T2-weighted turbo spin echo magnetic resonance (MR) images from N=10 (7 F) pre-surgical AIS patients. Participants were 12 to 18 (mean 14.82 ± 1.65) years of age with a median Risser sign of 4 (IQR 3-4). The cohort included Lenke 1 to 6 curves, with the main structural Cobb angle ranging from 45 to 71 degrees.

The disc and nucleus pulposus (NP) were manually segmented in 3D Slicer after resampling all MR images to a voxel size of $0.1 \times 0.1 \times 1.0$ mm (**Fig 1A**). The multi-slice segmentations were reconstructed to form 3D models of the disc and NP. Each participant had 8 to 14 discs segmented (total number of discs in study = 106) which spanned the main curve and often included the compensatory curve if one was present.

Disc wedge was calculated by fitting planes to the superior and inferior surfaces of each disc (**Fig 1A**). The arc cosine of the dot product of the normal unit vectors of each plane was used to calculate the disc wedge. Vertebral wedge was similarly computed for the adjacent vertebrae. A wedge fraction was calculated to determine relative contribution of the disc to the total spinal curvature. A transverse symmetry index was calculated as the area of overlap of the mirrored left and right sides of the disc normalized to the total area of the disc (**Fig 1A**). The NP offset was defined as the Euclidean distance between the centroids of the disc and NP in the coronal plane (**Fig 1A**). Balance distance was calculated as the orthogonal distance between the disc centroid and the mean of the C7 vertebral plumb line and the central sacral vertical line (balance line, **Fig 1A**).

RESULTS:

Across all patients, vertebral wedging accounted for the majority of coronal plane curvature (67.4%), but disc wedging was substantial, contributing $32.6 \pm 9.4\%$ to the total. A moderate and significant positive correlation was observed between the balance distance and disc wedge ($R^2 = 0.513$, $p < 0.001$, **Fig 1B**). The centroid of the NP was consistently displaced toward the convexity of the scoliotic curve which was found to be moderately correlated with the disc wedge ($R^2 = 0.521$, $p < 0.001$, **Fig 1C**). In addition, disc wedge was inversely correlated with the symmetry index ($R^2 = 0.341$ & 0.290 , $p < 0.001$). These findings suggest that the scoliotic disc experiences a consistent three-dimensional deformity that is coupled across planes and tissues.

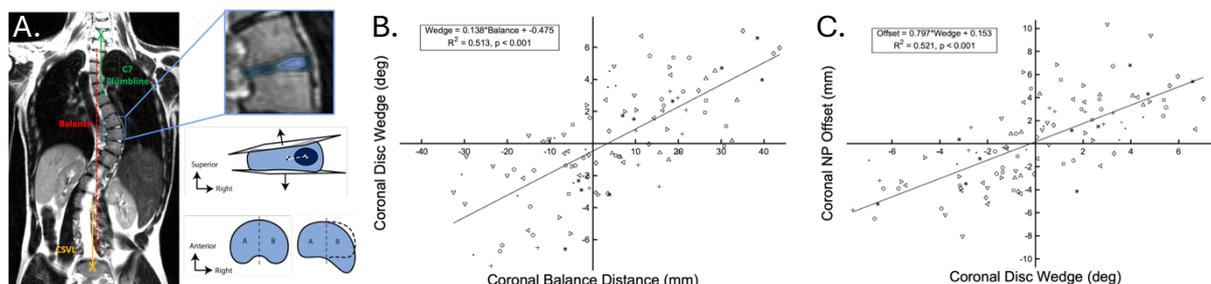


Figure 1. A) Coronal view from an MR scan of an AIS participant. The balance line is indicated on the MR image along with a representative disc and NP segmentation. The disc wedge, NP offset, and transverse symmetry metrics are shown visually. B) Disc wedge is correlated with balance distance. C) NP offset is correlated with disc wedge.

DISCUSSION:

This study provides quantitative evidence that the disc in AIS undergoes a 3D structural transformation. The disc wedge, loss in the centralization of the NP, and the asymmetry developed along the anterior-posterior axis in the transverse plane suggest that the mechanics of the scoliotic disc will differ from non-scoliotic discs which tend to have a more centralized NP, lack coronal plane wedging, and are largely left-right symmetric in the transverse plane. The magnitude of this mechanical asymmetry and its role in promoting or countering the deformity remain unknown. The correlation between the balance distance, which effectively acts as a moment arm, and disc wedge is consistent with mechanically driven growth modulation. While differential growth of the disc may occur, it is unclear if the observed structural changes are due to reversible poro-visco-elastic deformations, degeneration and damage, or growth modulation of the disc.

CLINICAL RELEVANCE:

As vertebral body tethering and other motion-preserving techniques become more widespread, understanding the biomechanical state of the disc prior to treatment is essential. This study demonstrates that discs in AIS undergo significant structural changes and nucleus migration, which may influence treatment response and long-term disc health.

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